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TEMPERATURE COEFFICIENT MEASUREMENTS ON A CRITICAL MOCK-UP OF EBR-I

by

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DISCLAIMER

ACKNOWLEDGEMENT

This work was performed by the Idaho Division of Argonne National Laboratory, following a suggestion of J. R. Dietrich, now with General Nuclear Engineering Corporation. Details of the experimental procedure were formulated by D. Okrent of ANL and B. Cerutti, who is at GNEC now. Many members of the Idaho Division as well as C. Branyan of APDA contributed to the experimental work. The project was under the general direction of F. W. Thalgott.

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ABSTRACT

A rough mock-up of the EBR-I reactor was built in the ZPR-III critical assembly machine, with resistance heaters in the core and inner blanket. The variation of reactivity with core temperature was observed. Lateral expansion was measured as the core was heated. A temperature coefficient of -0.42 inhour per degree Centigrade was observed when the core alone was heated, and -0.72 inhour per degree Centigrade was observed when the core and inner blanket both were heated. Essentially all of these coefficients are attributable to volume expansion.

INTRODUCTION

The EBR-I, a sodium-cooled fast breeder reactor, was known to have a positive temperature coefficient of reactivity under certain circumstances. For example, in the final experiment on the EBR-I core, the reactor was placed on a 60-second positive period at low power (9 watts) with zero coolant flow. The period decreased during the next several minutes, until finally a period estimated at about 0.4 second was reached.[1] This confirms that positive reactivity was added to the reactor as heat was generated in the core, as previously reported by Lichtenberger, et al.[2] The lack of coolant flow during this experiment caused such heat as was generated to be confined mostly to the core and inner parts of the blanket. Under normal operation, however, with coolant flow through the core and inner blanket, the steady-state temperature coefficient of the reactor as a whole was comfortably negative.

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[1] W. H. Zinn, Nucleonics 14, (6), 35 (1956). See also R. Brittan, "Some Problems in the Safety of Fast Reactors," ANL-5577, and Twentieth Semi-Annual report of the AEC, p. 45 (July, 1956).

[2] H. V. Lichtenberger, et al., "Progress Report on the Experimental Breeder Reactor, April 1, 1951 through January 31, 1953," ANL-5023 (1953).

Several possibilities have been suggested as sources of the positive temperature coefficient. First, a nuclear Doppler effect, related to the broadening of fission resonances at elevated temperatures,[3] would result in some positive contribution to the temperature coefficient. Attempts have been made to calculate the magnitude of such an effect,[4] but no experimental confirmation of the calculation for an assembly of the EBR-I type is available. The calculated value of Doppler coefficient of EBR-I is about 5×10^{-6} $\Delta k/k$ per degree Centigrade at 20°C.

Second, a mechanical effect, such as the inward bowing of fuel rods in a non-uniform temperature field, might be responsible for the positive reactivity coefficient. It has been calculated that radial contraction of as little as 2×10^{-4} inch per degree Centigrade average core temperature rise could cause the reactivity changes observed in the initial phases of the EBR excursion.

Moreover, it had been suggested that, either because of a Doppler effect in U^{235}, or because of mechanical effects such as rod bowing, the temperature coefficient for core heating alone might be positive, despite the fact that the over-all temperature coefficient of the reactor was negative.

In order to study the temperature coefficient in a more controlled fashion, the ZPR-III critical assembly facility was used to mock-up the composition and approximate dimensions of EBR-I. The temperature effects observed in this mock-up are the subject of this report. Provisions were made for heating the core while insulating the inner blanket, or heating the core and parts of the inner blanket while insulating the rest of the assembly. An instrument for measuring the lateral expansion of the heated portion of the reactor was also installed. Thus it was proposed to measure a temperature coefficient of the core alone, or of the core and inner blanket together, and to make an effort to compare these with the coefficients due to volume expansion. Since rod bowing is not a factor in the ZPR-III, any unaccountable temperature effects might then represent, within the accuracies of the calculations and measurements, upper limits of the nuclear Doppler effects.

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[3] Feshbach, Goertzel and Yamauchi, "Estimation of Doppler Effect in Fast Reactors," Nuclear Science and Engineering, 1, (1), 4 (March, 1956).

[4] Yamauchi and DeFelice, "Doppler Temperature Coefficients of Reactivity in Fast Reactors," NDA-14-82 (1955).

This experiment was a supplement to Kato's measurement of Doppler effect[5] rather than a substitute method. Kato determined the Doppler effect on a small sample, relatively free from expansion effect, and extrapolated to the mass of the whole core. With the critical mock-up, on the other hand, a combination of Doppler and expansion effects on a large section of the reactor (core or core plus blanket) was measured. Thus in the EBR-I mock-up, no extrapolation in size was required, but considerable correction for expansion was necessary before any Doppler effect could be estimated.

ZPR MOCK-UP LOADING

The ZPR-III facility has been described by Cerutti, et al.[6] A diagram of the loading used in the EBR-I mock-up is shown in half-plan view in Figure 1. The compositions used in the ZPR to simulate the EBR regions are given in Table I.

Table I

Regions	ZPR Composition, by Volume	
Core	U^{235}	50.0 %
	$U^{234}+U^{236}+U^{238}$	3.60%
	Aluminum	11.63%
	Stainless Steel	12.60%
Inner Blanket	U^{235}	0.10%
	U^{238}	49.59%
	Aluminum	11.48%
	Stainless Steel	17.46%
Plenum	Stainless Steel	47.87%
	Aluminum	18.68%
Cup	U^{235}	0.19%
	U^{238}	82.23%
	Stainless Steel	7.31%
	Aluminum	2.62%
Structure plus NaK	Stainless Steel	49.15%
	Aluminum	22.19%
Reflector plus NaK	U^{235}	0.09%
	U^{238}	41.34%
	Aluminum	25.43%
	Stainless Steel	7.31%

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[5] Kato and Butler, "Measurement of the Uranium Doppler Effect in a Fast Assembly," ANS Winter Meeting, December 12, 1956.

[6] Cerutti, Lichtenberger, Okrent, Rice and Thalgott, "ZPR-III, Argonne's Fast Critical Facility," Nuclear Science and Engineering 1, (2), 126 (May, 1956).

Figure 2 shows a diagram of the interface of the two halves of the assembly, looking at the fixed half. The core is simulated by a rectangular, rather than a cylindrical, region.

A typical drawer loading in the heated region is shown in Figure 6. The densities of the aluminum pieces were chosen to add up to the percentages given in Table I.

Figure 7 is a photograph of the interface and Figure 8 shows the outside of one half, including the heater connections at the back of the drawers.

The critical mass of the assembly with core heaters in place was 45.36 kg U^{235} at 25°C. Control rod number 10, located in drawer 1N14, was calibrated as shown in Figure 9. In the construction of Figure 9, observed periods corresponding to control rod positions were translated to reactivity in inhours, using the delayed neutron data of Hughes, et al.[7] Core material at the outer edge of the core was found to be worth approximately 270 inhours per kilogram of U^{235}.

Heaters

Two arrangements of heaters were used as shown in the interface views, Figures 3 and 4.

Core heating. Figure 3 shows an arrangement of heaters in the core region alone, with coolant channels around the core. During operation, air at room temperature was blown through these channels to prevent heat transfer sideways to the blanket. A layer of aluminum oxide also helped to prevent losses of heat out the sides of the core.

Core plus inner blanket heating. Figure 4 shows an alternate arrangement of heaters throughout the core and inner blanket, with coolant and insulating material moved out beyond the heaters. This arrangement required slight changes in critical mass and in control rod calibration, but the loading was still essentially the same as shown in Figures 1, 2, and 6.

In both of the above arrangements the heaters were constructed as shown in Figure 5. The ceramic insulation over the copper leads and nichrome heaters extended the full length of the assembly, so that connections could be made at the back.

The moving half of the assembly in each case appeared the same as in Figure 3 or 4, respectively, except that deflectometer tubes and thermocouples were not present.

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[7]Hughes, Dobbs, Kahn, and Hall, Phys. Rev. 73, 111 (1948).

Deflectometer

Tubes for the deflectometer extended sideways through the blanket, $1\frac{1}{2}$ inches from the interface at the mid-plane of the reactor. The deflectometer consisted of 1/2 inch Vycor tubes which were held adjacent to the outer loading pieces in drawers 1P15 and 1P17 by springs. The outer end of the Vycor tube was attached to a needle valve through which compressed air at constant pressure was flowing. The pressure drop through the needle valve actuated an indicator calibrated to 0.0001 inch. This device is manufactured by the Federal Products Corporation of Providence, R.I.

Thermocouples

Iron-constantan thermocouples were located at the bottom of drawers in row P, $1\frac{1}{2}$ inches from the interface, in the locations indicated in Figures 3 and 4. Each thermocouple was read against an individual ice junction on a potentiometer accurate to 0.02 mv (about 0.4°C).

DETERMINATION OF TEMPERATURE COEFFICIENTS

The procedure generally used to determine the temperature coefficient of reactivity of the core was as follows:

1. The reactor was made critical at a power level of a few hundredths of a watt.

2. Voltage was applied to the heaters imbedded in the core sufficient to make the average core temperature rise at about one to two degrees Centigrade per minute.

3. As temperature rose, the calibrated control rod was moved inward in small steps so that the reactor remained just critical (within ±2 inhours).

4. At convenient intervals (about every ten minutes) all thermocouples were quickly read, and the control rod position and deflectometer readings were simultaneously recorded. The same data were recorded on cooling.

5. From the position of the calibrated control rod, reactivity can be determined as a function of any of the thermocouple temperatures, as plotted in Figures 10 to 17. Temperature profiles at various times during the heating and cooling are shown in Figures 18 and 19. Deflectometer readings are plotted against the temperatures at the center of the assembly in Figures 20 and 21.

EXPERIMENTAL RESULTS

In Figures 10 to 13 reactivities during two separate core-heating runs are distinguished by circles and triangles. No normalization was used, so the figures give an indication of the reproducibility of these data. Points located by open circles or triangles were obtained while the core was being heated, and those located by solid circles or triangles were obtained while it was cooling. The displacements of the heating curves from the cooling curves indicate that, at the start of the experiment, some heating occurred before any measurable loss in reactivity took place. Then, when the heaters were turned off, some cooling occurred before any reactivity was regained. Thermocouple number seven, data for which are plotted in Figure 13, was located immediately next to a heater and consequently shows this effect most strongly. The thermocouples of Figures 10 to 13 were located as shown in Figure 3.

Figures 14 through 17 show similar plots for the case where both core and inner blanket were heated. For this group of figures, the pattern of heaters and thermocouples is shown in Figure 4. The same scheme of presenting two separate runs by circles and triangles, with the heating and cooling sections distinguished by open and solid symbols, is used in these figures. The reproducibility of two separate runs was poor during the initial warm up, but as heating continued good agreement was achieved.

Temperature profiles at various times are shown in Figure 18 for core heating and in Figure 19 for core and inner blanket heating. To construct these curves, the thermocouple readings in the neighborhood of one of the heaters were used to pattern the detailed temperature peak near this heater. This peak was then used to infer the temperature pattern around all the other heaters. Other thermocouples scattered through the assembly cross section demonstrated the symmetry of the temperature pattern. Thermocouples placed behind the center of the core indicated the extent of axial thermal leakage. Their readings are also shown on Figures 18 and 19. The temperature profiles showed marked peaks during the heating, but these peaks were dissipated during cooling. Unfortunately, the attractive temperature profile during cooling could not be used very successfully to determine a temperature coefficient of reactivity, because apparently there was some delay before the core pieces returned to their cold configuration. The heating curves were therefore used to determine temperature coefficients, although this necessitated the assignment of some representative temperature to the core during a period when the local temperatures showed considerable variation. A temperature which could be used to represent the entire core, with a minimum of hysteresis and good reproducibility, was the reading from the central thermocouple No. 4 (in the case where the core alone was heated,) and from No. 9 (in the case where core and inner blanket both were heated.)

Figure 20 shows how the deflectometer readings varied with the center temperature for the assembly in which the core alone was heated. The deflectometer measured the expansion at different positions in the two runs. In the first run, denoted by circles, the Vycor tubes were held against the outer pieces of core material in drawers 1P15 and 1P17, so that the lateral expansion of the core itself was determined. In the second run, denoted by triangles, the Vycor tubes were held against the outer sides of the 1P15 and 1P17 stainless steel matrix tubes, thus measuring the expansion of the three central matrix tubes. Here again, open symbols represent heating while solid symbols indicate cooling.

In Figure 21, the variation of deflection with the central core temperature is shown for two runs where both core and inner blanket were heated. In these runs the Vycor tubes of the deflectometer were held against the outer plates in drawers 1P13 and 1P19.

In Table II coefficients of reactivity and of deflection are given, based on the best straight lines that could be drawn through the portions of the curves where temperature was rising. The data are based on temperatures at the center of the core.

Table II

Experimental Temperature Coefficients

Heated Region	Coefficient of Reactivity Inhour/Degree C	Coefficient of Lateral Expansion Inch/Degree C
Core	-0.42	1.10×10^{-4} (core expansion)
		0.77×10^{-4} (matrix expansion)
Core plus Inner Blanket	-0.72	1.86×10^{-4} (core plus inner blanket expansion)

ESTIMATION OF EXPANSION EFFECTS

UNIVAC calculations on 6 groups in 3 regions have been performed to estimate the reactivity effect of expansion of a sphere with composition similar to those used in the mock-up. The three regions consisted of an 11-cm radius core, a 25.38-cm outer radius low-density blanket, and a 50-cm outer radius full density blanket. The change in reactivity resulting from an expansion of the core accompanied by an equivalent compression of the inner low density blanket was computed. The outer radii of the blankets remained unchanged at 25.38 and 50 cm. This situation is thought to be analogous to the behavior of the mock-up, where the core expands with temperature, but outside dimensions of the blanket are unchanged. Some compressive deformation probably occurs in the inner blanket.

The calculated reactivity change was

$$\frac{\Delta k}{k} = -0.3 \frac{\Delta V}{V} , \tag{1}$$

where V refers to the core volume.

If it is assumed that the same coefficient would apply to a square cylinder, with radial expansion accounting for twice the reactivity effect of axial expansion, then, for the cylinder,

$$\frac{\Delta k}{k} = -0.6 \frac{\Delta r}{r} \quad \text{for radial expansion} \tag{2}$$

and

$$\frac{\Delta k}{k} = -0.3 \frac{\Delta L}{L} \quad \text{for axial expansion .} \tag{3}$$

In subsequent calculations, where an equivalent radial core expansion coefficient was required, the measured lateral core material coefficient, 1.10×10^{-4} inch per degree Centigrade (a figure that may be slightly high for this purpose because of the clearances in the vertical direction), was used.

If equations (2) and (3) are applied to a cylinder 8.08 inches long and with a radius of 3.40 inches (the equivalent radius of the mock-up), they become

$$\frac{\Delta k}{k} = -7 \text{ inhours per mil of radial expansion} \tag{4}$$

and

$$\frac{\Delta k}{k} = -1.5 \text{ inhours per mil of axial expansion ,} \tag{5}$$

using the relation that 400 inhours equals 1% reactivity.

Using the lateral core expansion coefficient of 1.1×10^{-4} inch per degree Centigrade,

$$\left(\frac{\Delta k}{k \Delta T}\right)_{\text{lateral and vertical}} = -7 \times 0.11 \times 1/2 = -0.38 \text{ inhour/degree}$$

is the coefficient for the reactivity effect of both lateral and vertical expansion combined.

In the estimation of the axial expansion, it was assumed that the expansion coefficient of uranium measured on representative plates would satisfactorily approximate the axial expansion of the core in our mock-up. This is because in the mock-up the plates are restrained, end to end, under spring pressure, and the total core should expand outward from the middle more or less as calculated. Across the direction of rolling of the uranium plates, which is the axial direction, the expansion coefficient of uranium was found to be 18×10^{-6} per degree Centigrade. Thus with the axial length of 8.08 inches, equation (5) yields

$$\left(\frac{\Delta k}{k \Delta T}\right)_{\text{axial}} = -0.22 \text{ inhour per degree Centigrade.}$$

The total expansion effect on reactivity therefore becomes about -0.60 inhour per degree Centigrade.

The calculated temperature coefficient of reactivity for the sphere, equation (1), was expected to be reliable to within about ten per cent. Among the principal uncertainties involved in applying this coefficient to the core mock-up are:

1. The somewhat uncertain effect of applying the results calculated for a sphere to the rectangular core used in the ZPR. In particular, the calculated coefficients apply to an isotropic expansion, while the experimental core is not isotropic. Compression of the inner blanket is certainly quite different in the axial direction from those in the lateral and vertical directions.

2. The assumption that the vertical expansion of the core was the same as the lateral expansion. Mechanical limitations prevented a measurement in the vertical direction.

In view of these uncertainties it is easily conceivable that the reactivity coefficient calculated for temperature expansion of the core mock-up is in error by thirty per cent.

The measured reactivity coefficient appears, from the reproducibility of the curves in Figures 10 to 17 and the consistency of their slopes, to be somewhat more reliable, perhaps within ten per cent.

The amount of reactivity coefficient not attributable to expansion of the core may therefore be expressed as the measured coefficient minus the calculated expansion coefficient, or

$$\left(\frac{\Delta k}{k \Delta T}\right)_{\text{core}} = -0.42\ (\pm 0.04) + 0.60\ (\pm 0.18) = 0.18\ (\pm 0.18) \text{ inhour}/^{\circ}\text{C}$$

Thus within the limits of accuracy of the experiment, there may be no unaccounted reactivity effects for core heating. Doppler effects, if present, were too small to be estimated by this procedure.

No UNIVAC calculation is currently available for a direct evaluation of the expansion effects when core and inner blanket both were heated. The inner blanket may be expected to have a reactivity worth approximately ten per cent of the core worth (from local reactivity worth measurements in this region). We have therefore assumed that the reactivity coefficient of expansion of the core plus inner blanket would be -0.66 (±0.20) inhour per degree Centigrade, ten per cent higher than the coefficient of the core alone. The measured coefficient from Table II, assuming a ten per cent uncertainty, was -0.72 (±0.07) inhour per degree Centigrade. This leaves for unassigned reactivity effect only -0.06 (±0.21) inhour per degree Centigrade for core and blanket heating, again indicating that Doppler effects are too small to be estimated by this procedure.

The observed differences in reactivity coefficient between the core and core plus inner blanket heatings were large. After subtraction of the rather uncertain volume expansion effect, however, the remainders were not conclusively different in the two cores. The blanket heating would be expected to contribute negative Doppler effects if any, so that the experimental results indicated a difference which is small and uncertain but in the right direction.

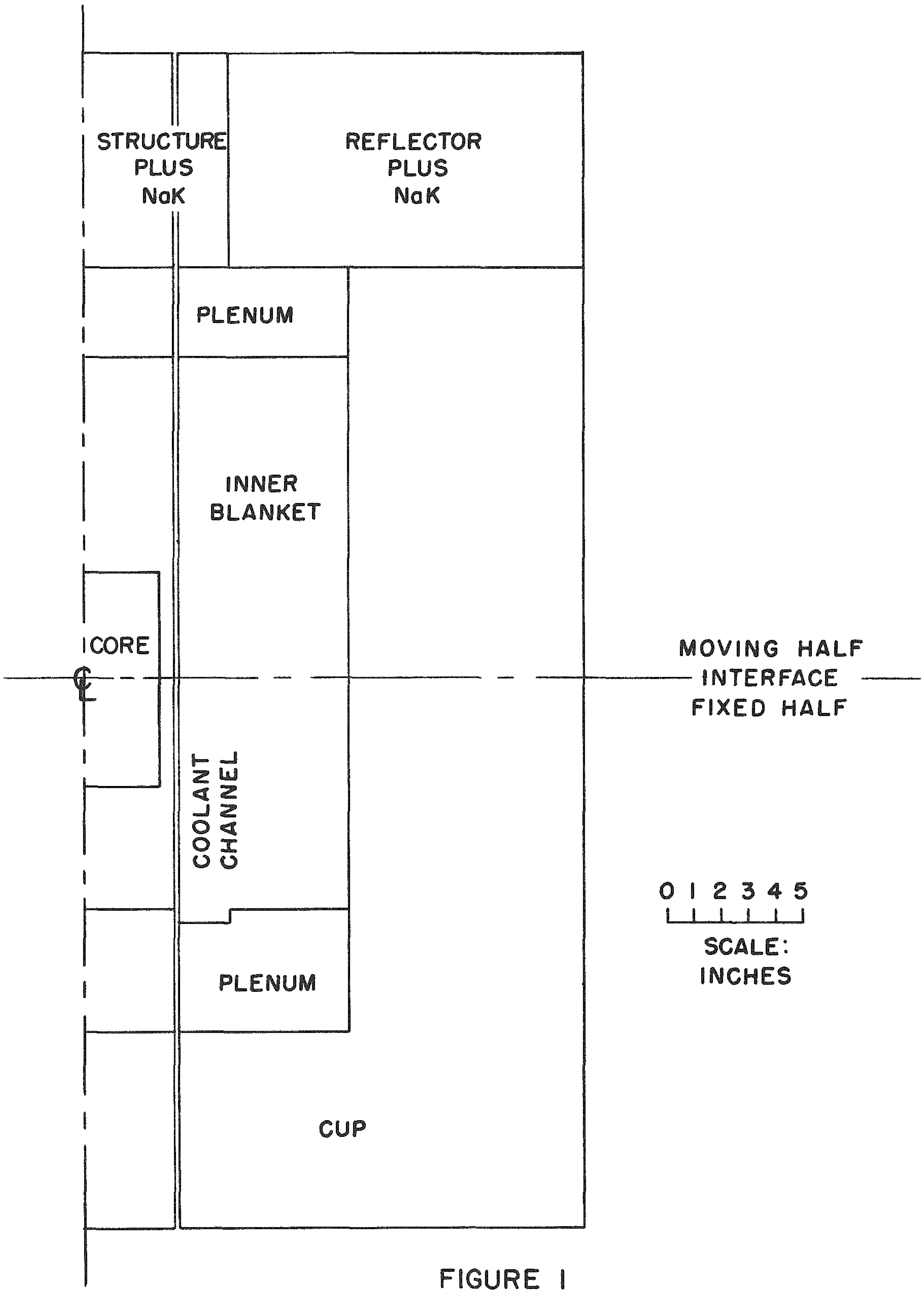


FIGURE 1

CROSS SECTIONAL VIEW FROM ABOVE OF ZPR-III LOADING TO SIMULATE EBR-I

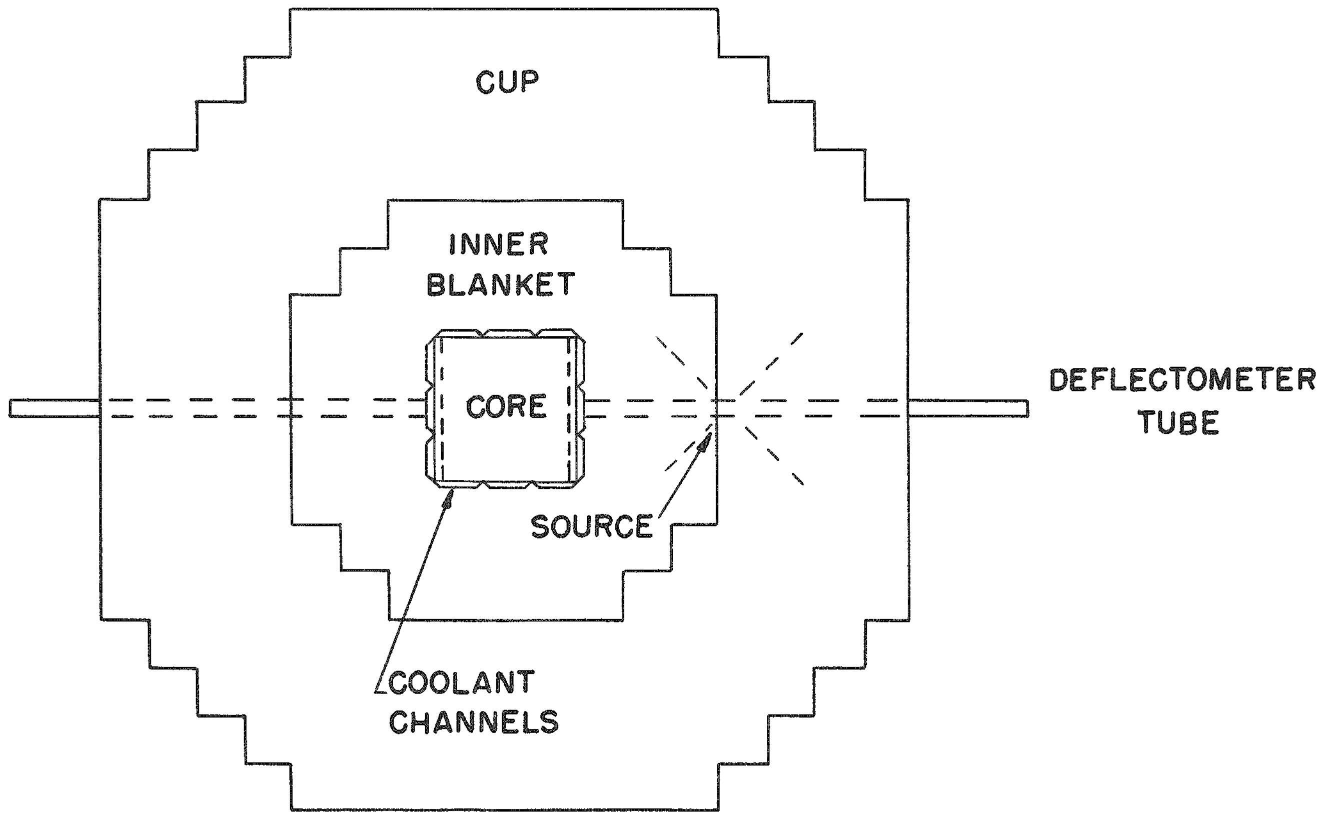
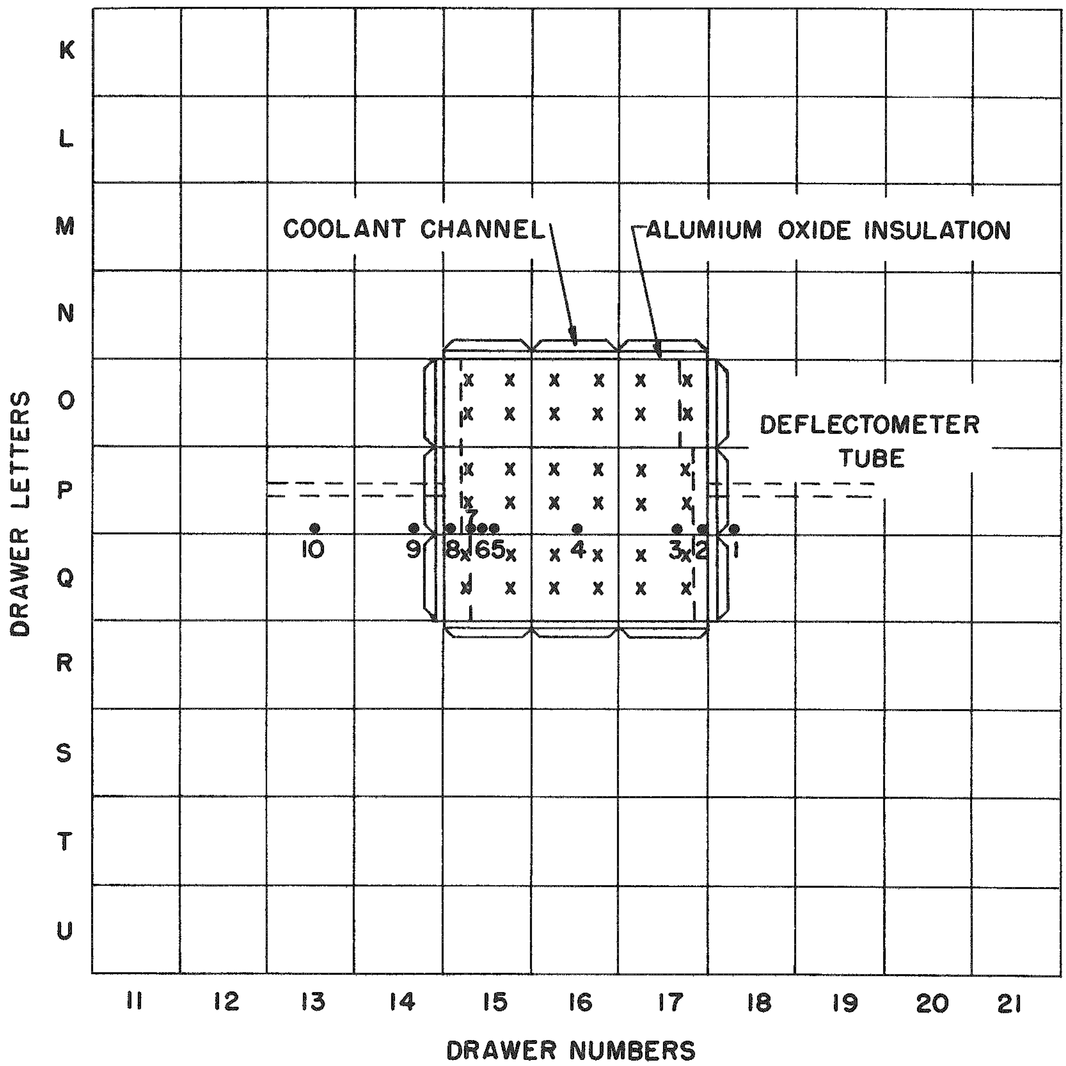


FIGURE 2
ASSEMBLY LOADING FOR CORE HEATING



x —HEATER

• — THERMOCOUPLE, 1-1/2" BACK OF INTERFACE, NUMBERED 1 TO 10 FROM RIGHT TO LEFT

FIGURE 3

CORE, FIXED HALF, HEATERS IN CORE ONLY.

THE VERTICAL DASHED LINES ARE THE BOUNDARIES OF THE FUELED REGION.

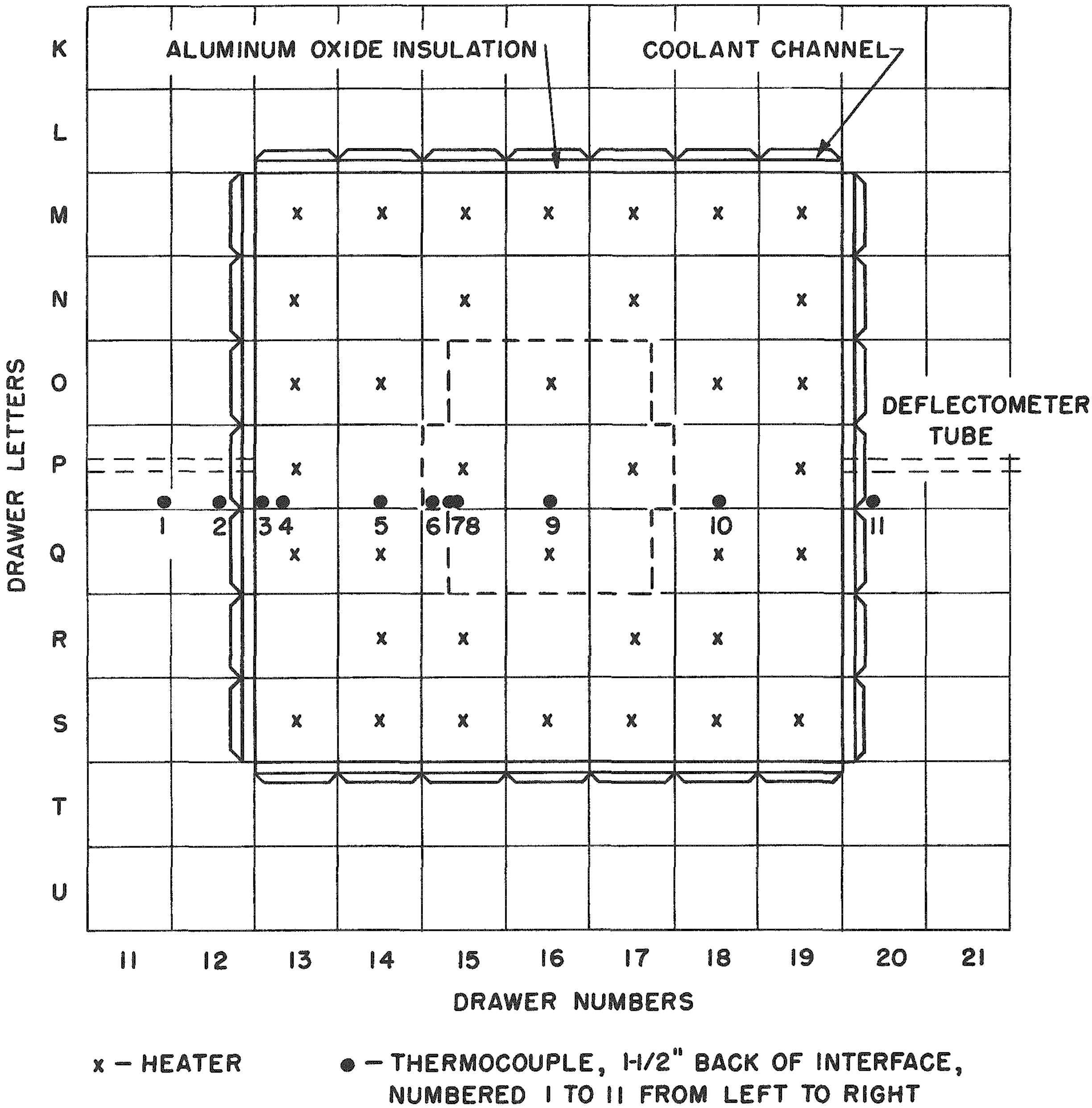


FIGURE 4

CORE, FIXED HALF, HEATERS IN CORE AND INNER BLANKET. THE DASHED LINES ARE THE BOUNDARIES OF THE FUELED REGION.

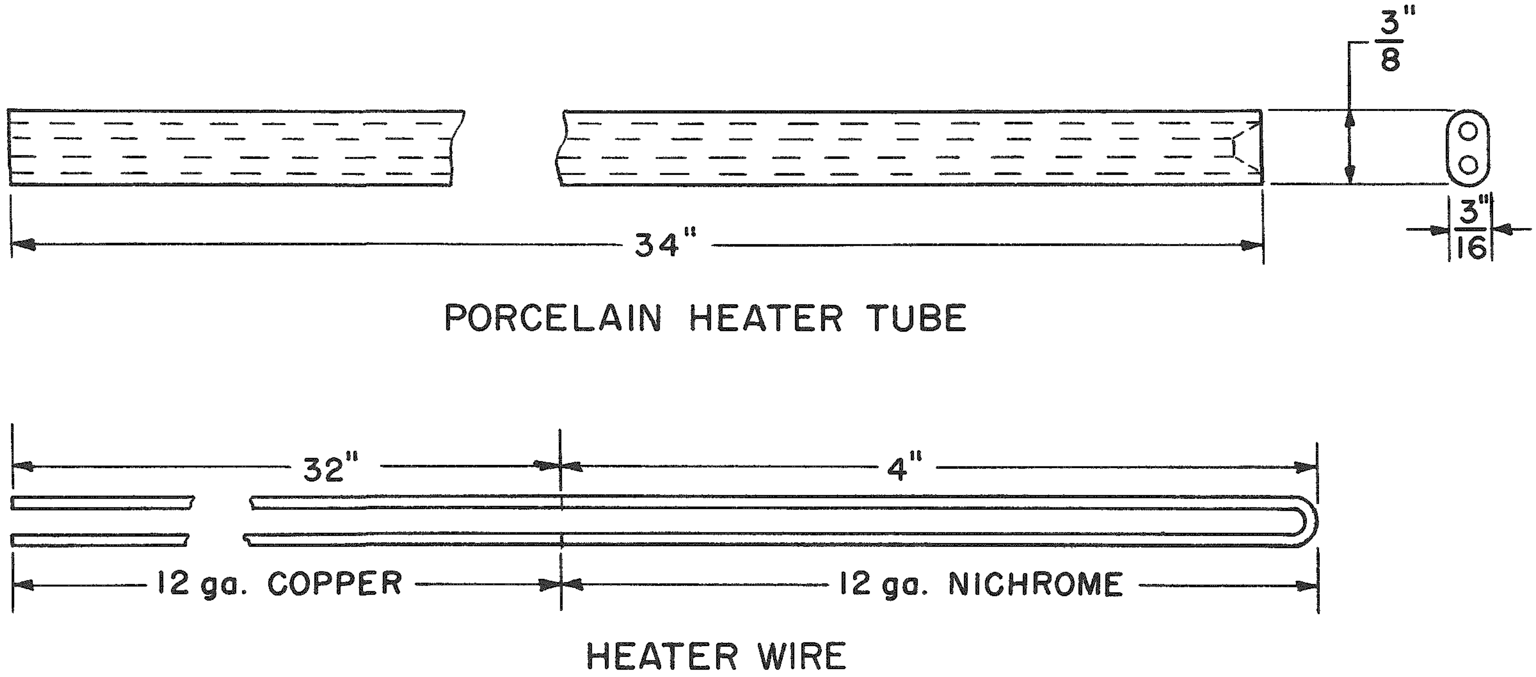

3"
8
34"
3"
16
PORCELAIN HEATER TUBE
32"
4"
12 ga. COPPER
12 ga. NICHROME
HEATER WIRE

FIGURE 5

	ENRICHED U-235	DEPLETED U	STAINLESS STEEL	DEPLETED U
	ENRICHED U-235	DEPLETED U	ALUMINUM	DEPLETED U
	ENRICHED U-235	STAINLESS STEEL	STAINLESS STEEL	DEPLETED U
	ALUMINUM	ALUMINUM	ALUMINUM	DEPLETED U
A	ALUMINUM, 1/16"	ALUMINUM, 1/16"	ALUMINUM, 1/16"	STAINLESS, 1/16"
	ENRICHED U-235	DEPLETED U	STAINLESS STEEL	DEPLETED U
	ENRICHED U-235	DEPLETED U	ALUMINUM	DEPLETED U
	ALUMINUM, 1/16"	ALUMINUM	STAINLESS STEEL	DEPLETED U
	ENRICHED U-235	DEPLETED U	ALUMINUM	DEPLETED U
	STAINLESS STEEL	STAINLESS STEEL	STAINLESS STEEL	DEPLETED U
	ENRICHED U-235	DEPLETED U	ALUMINUM	DEPLETED U
	ENRICHED U-235	DEPLETED U	STAINLESS STEEL	DEPLETED U
B	ALUMINUM, 1/16"	ALUMINUM, 1/16"	ALUMINUM, 1/16"	STAINLESS, 1/16"
	ALUMINUM	ALUMINUM	ALUMINUM	DEPLETED U
	ENRICHED U-235	DEPLETED U	STAINLESS STEEL	DEPLETED U
	ENRICHED U-235	DEPLETED U	ALUMINUM	DEPLETED U
	ENRICHED U-235	DEPLETED U	STAINLESS STEEL	DEPLETED U

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

INCHES FROM FRONT OF DRAWER

ASSEMBLY NO. 7

FIGURE 6

TYPICAL CORE DRAWER LOADING. HEATERS AND THEIR LEADS EXTEND THE FULL LENGTH OF THE DRAWER AT POSITIONS A AND B.

FILLER PLATE YES [X] NO [ ]

SPRING AT 4"

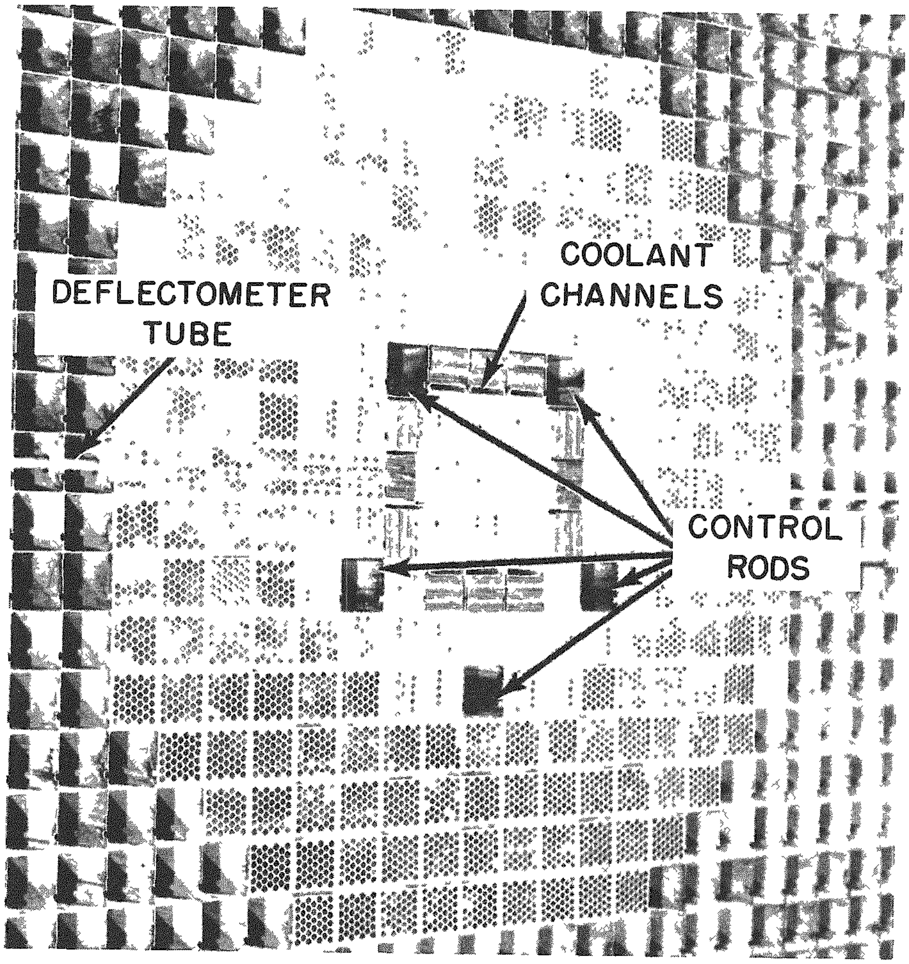


FIGURE 7
ZPR—III, INTERFACE

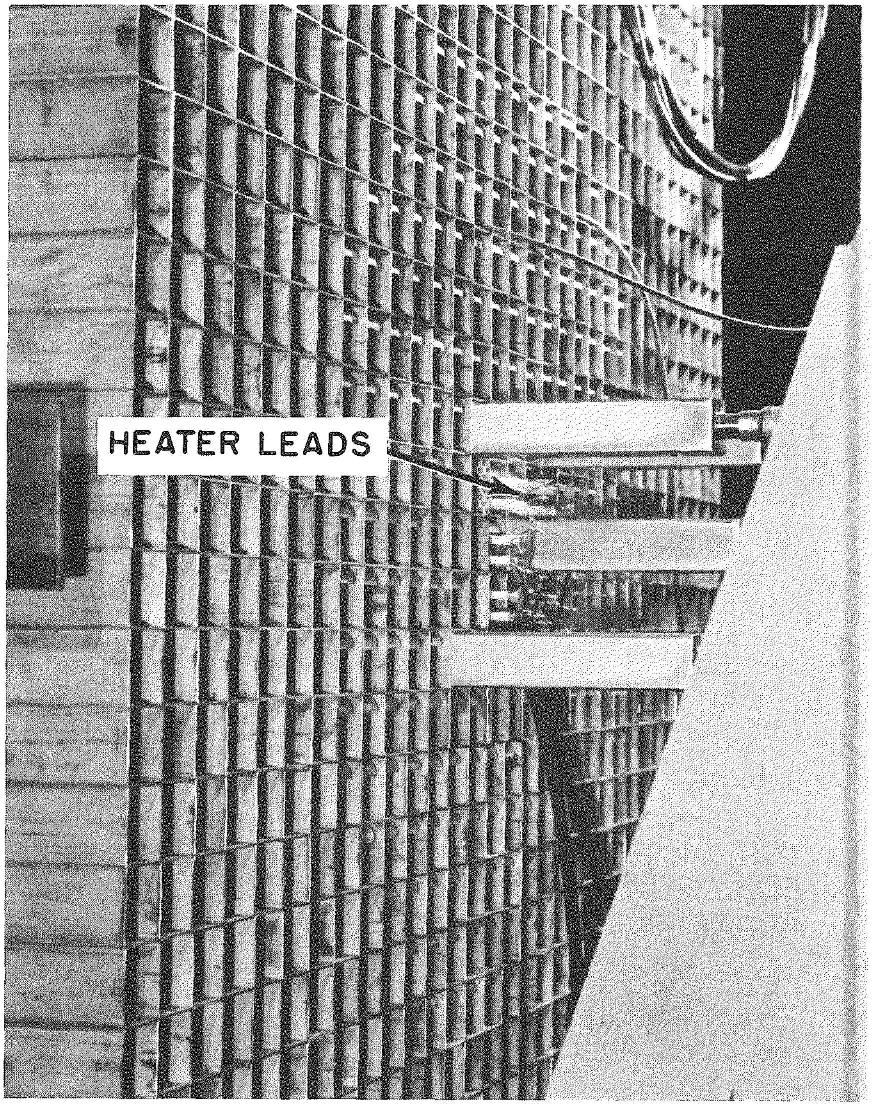


FIGURE 8
ZPR-III, REAR VIEW OF MOVING HALF

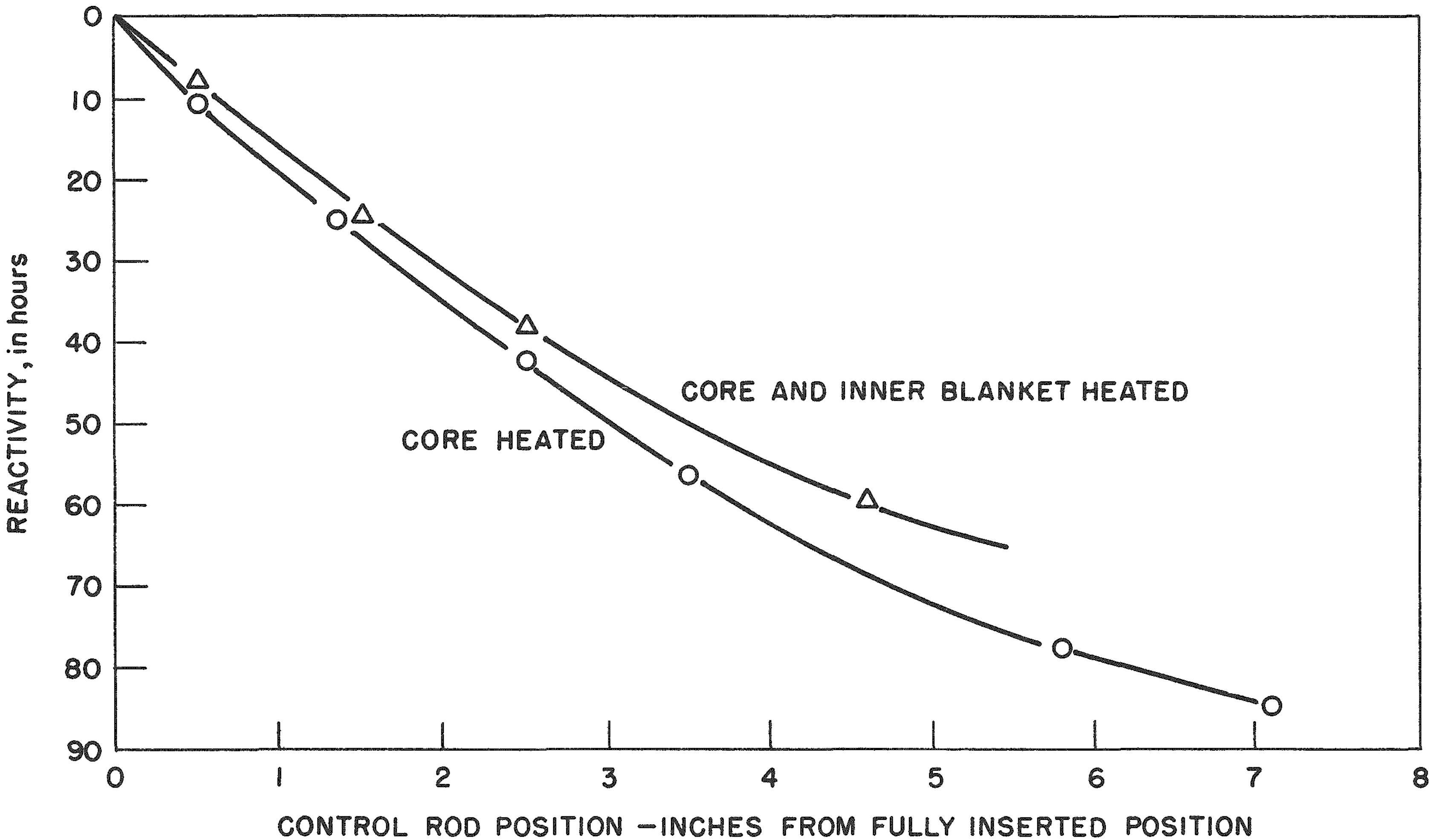


FIGURE 9
CONTROL ROD CALIBRATIONS

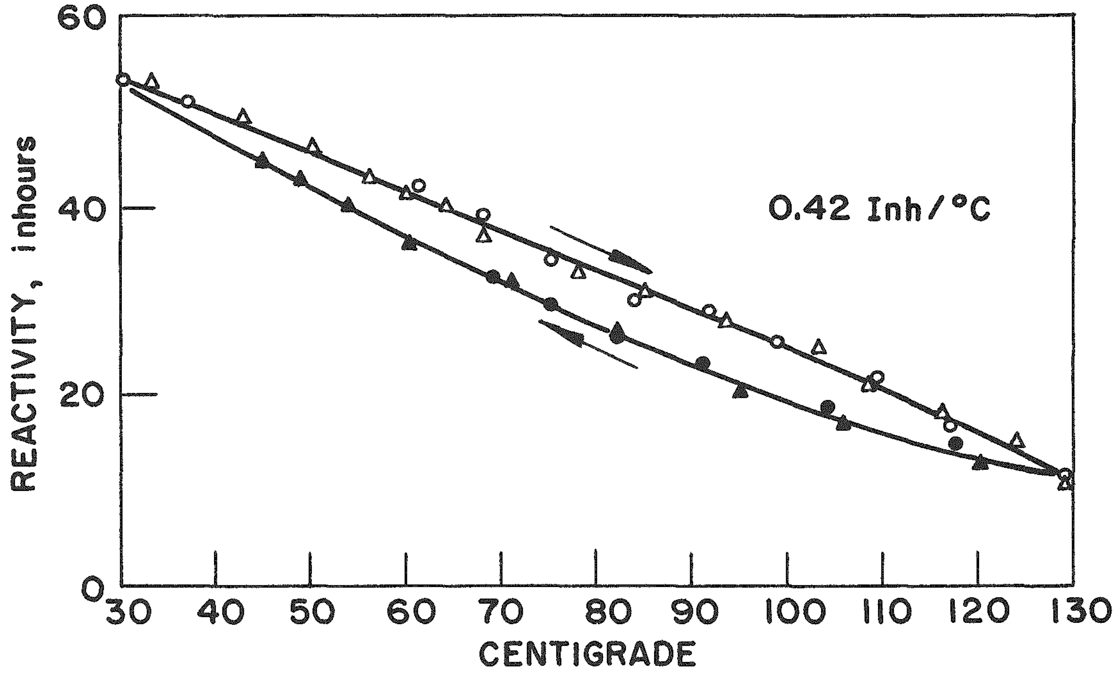


FIGURE 10
THERMOCOUPLE NO.4, CORE HEATING

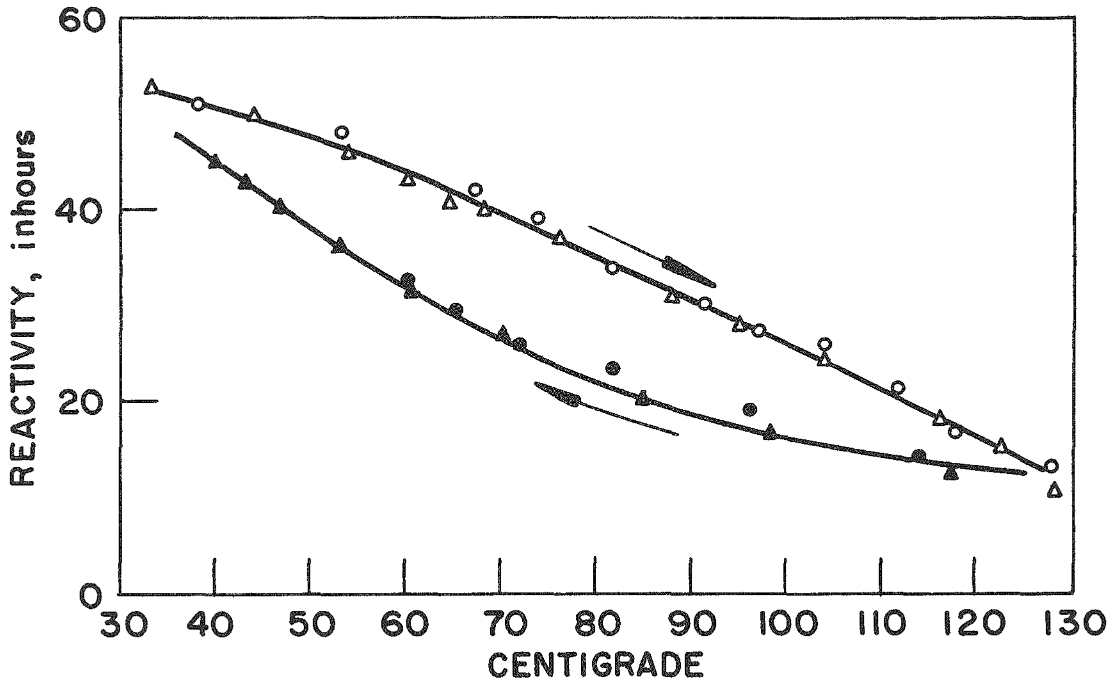


FIGURE 11
THERMOCOUPLE NO.5, CORE HEATING

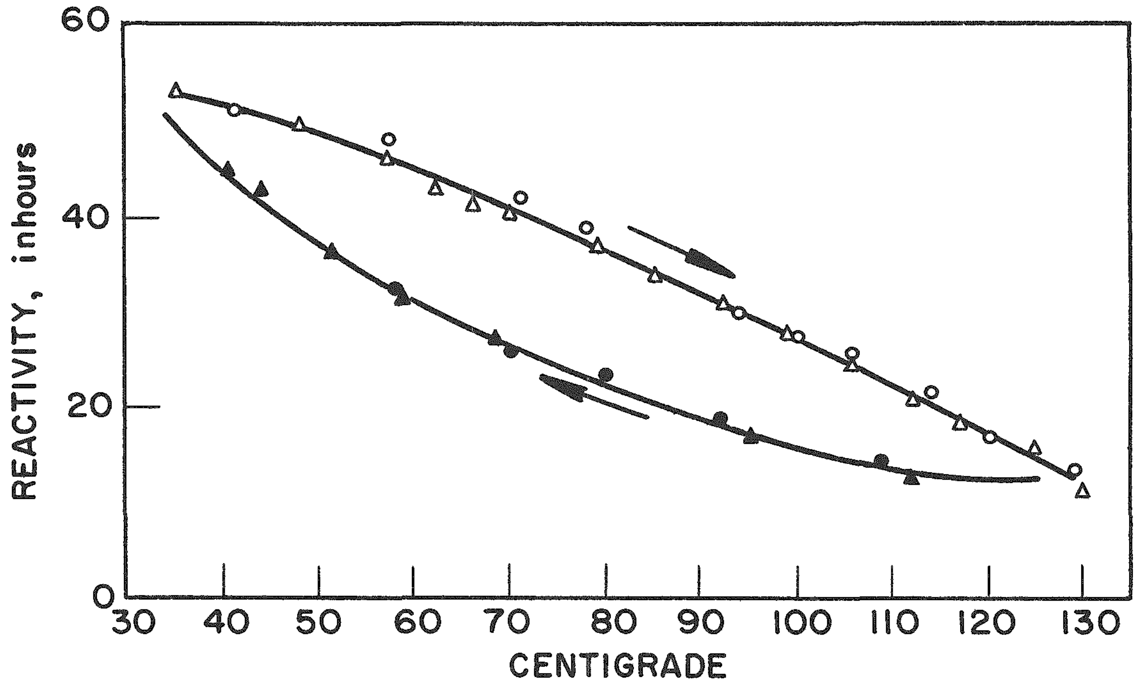


FIGURE 12
THERMOCOUPLE NO. 6, CORE HEATING

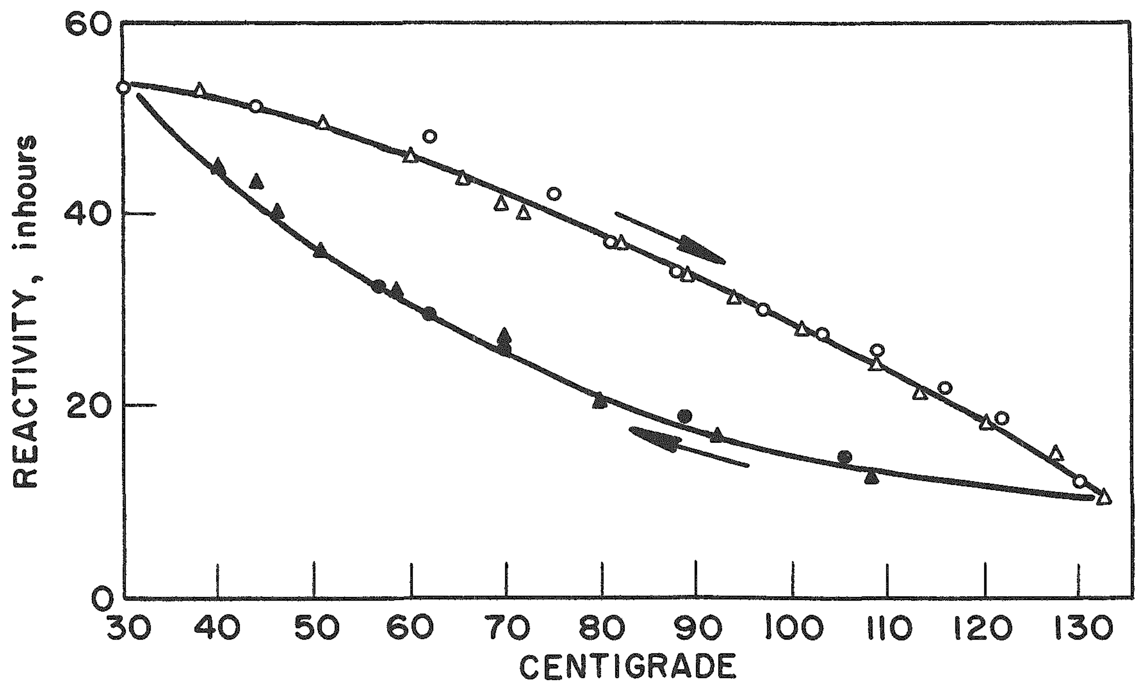


FIGURE 13
THERMOCOUPLE NO. 7, CORE HEATING

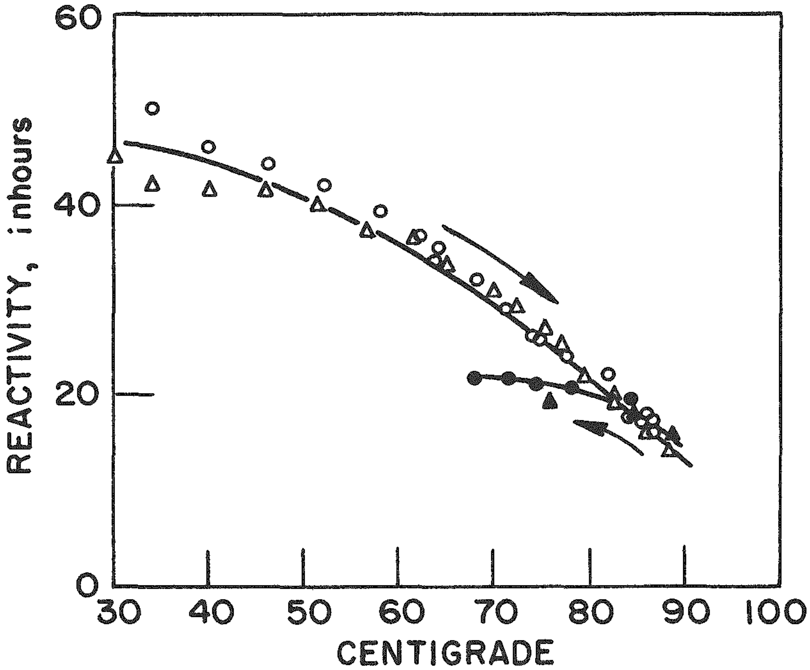


FIGURE 14
THERMOCOUPLE NO. 5, CORE
PLUS INNER BLANKET HEATED

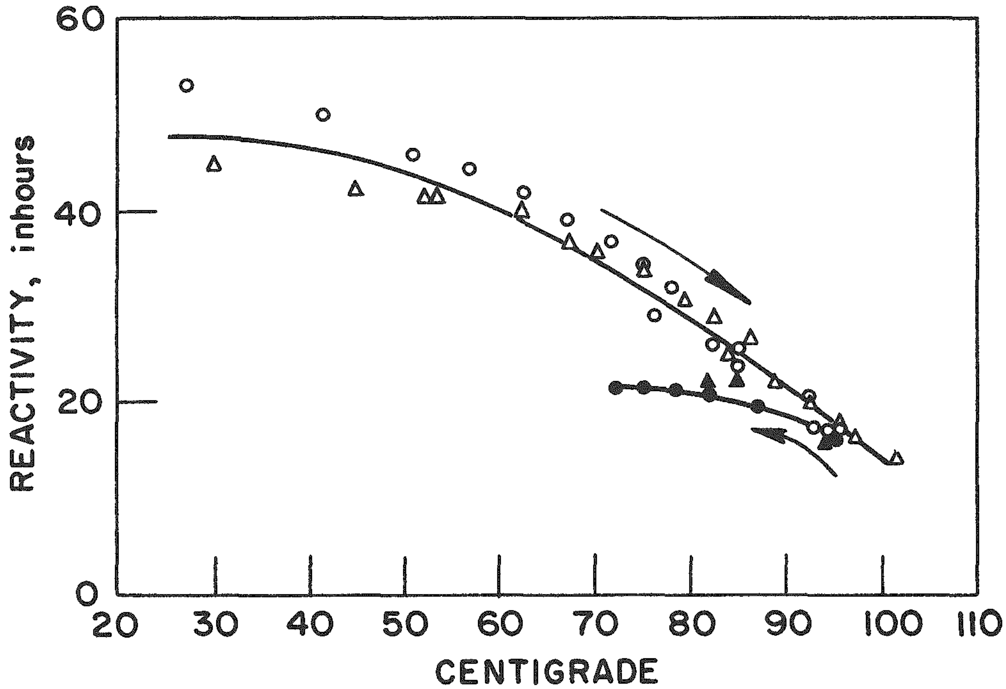


FIGURE 15
THERMOCOUPLE NO. 6, CORE
PLUS INNER BLANKET HEATED

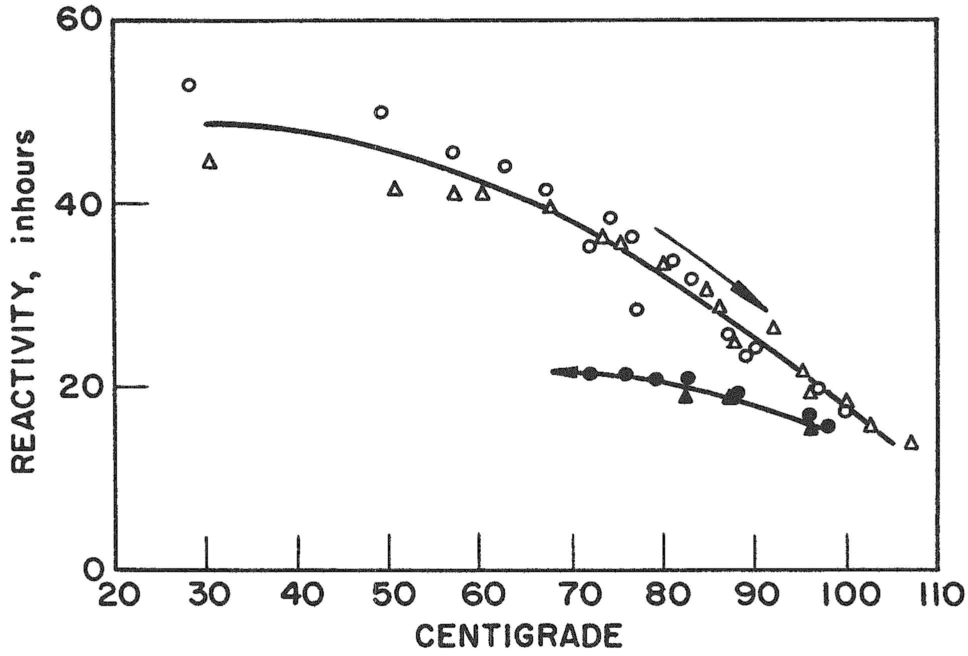


FIGURE 16
THERMOCOUPLES NO.7 AND 8, CORE
PLUS INNER BLANKET HEATED

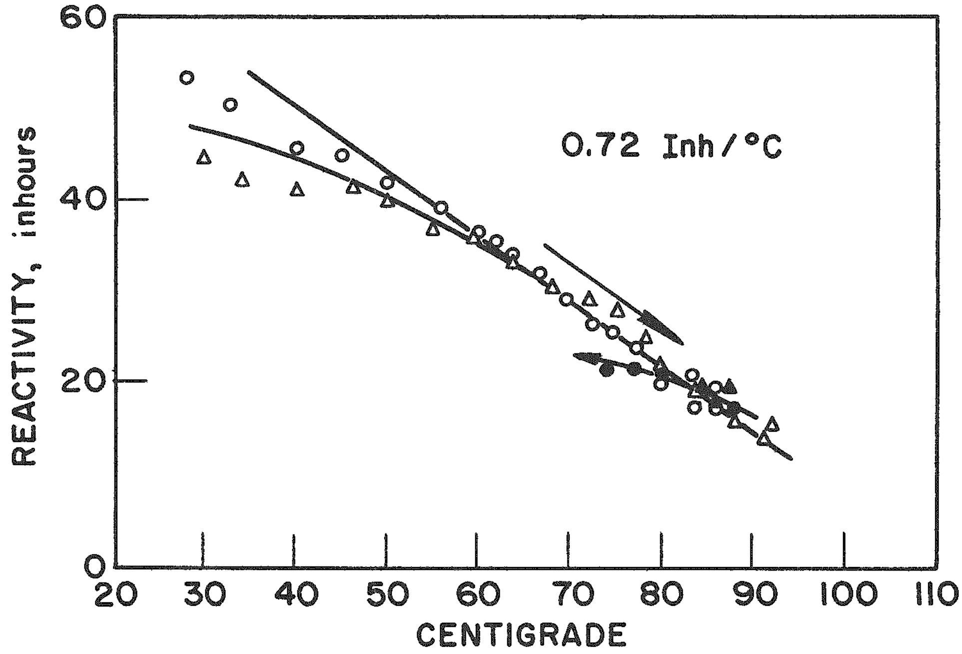


FIGURE 17
THERMOCOUPLE NO. 9, CORE
PLUS INNER BLANKET HEATED

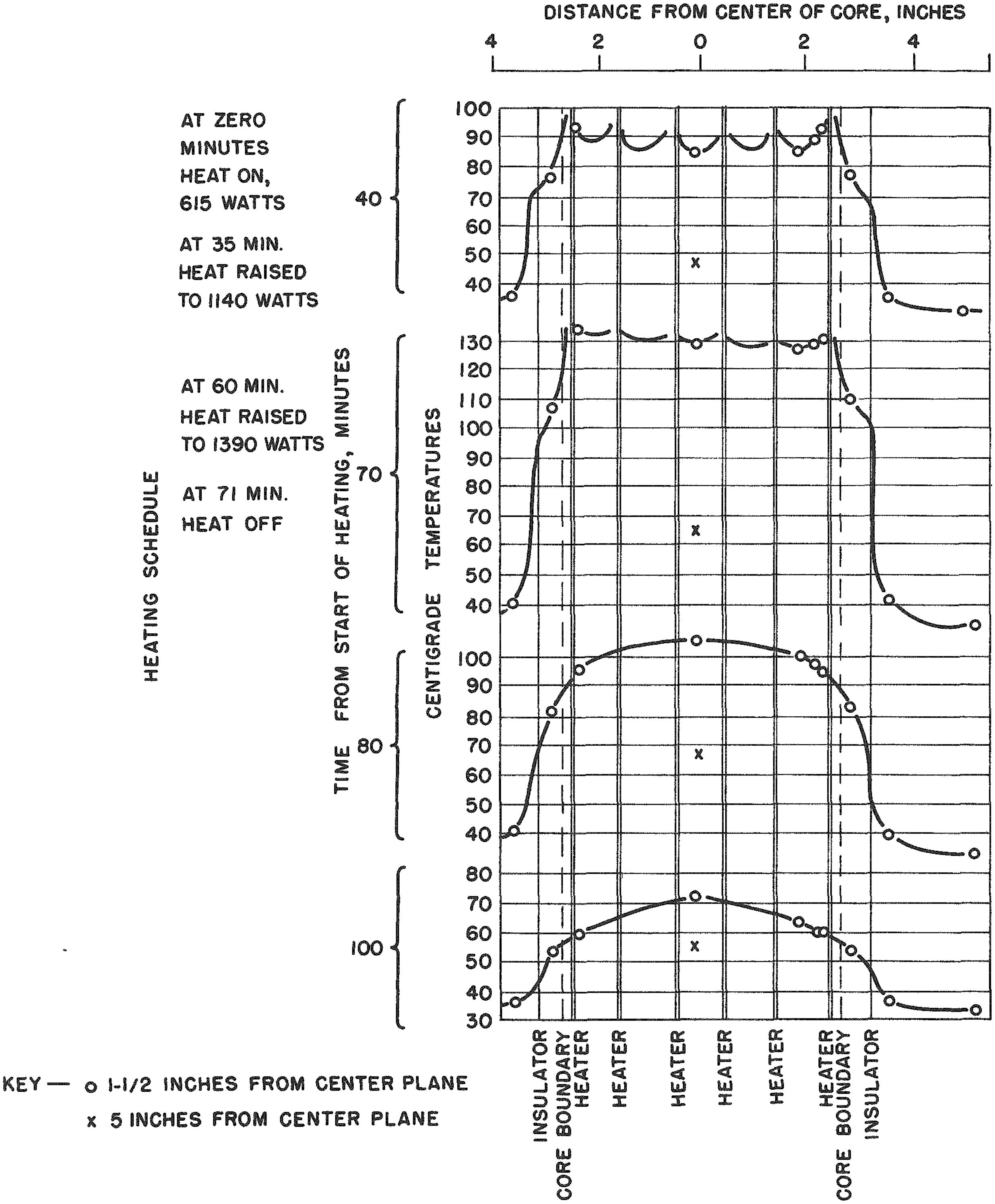


FIGURE 18

TEMPERATURE PROFILES — CORE HEATED

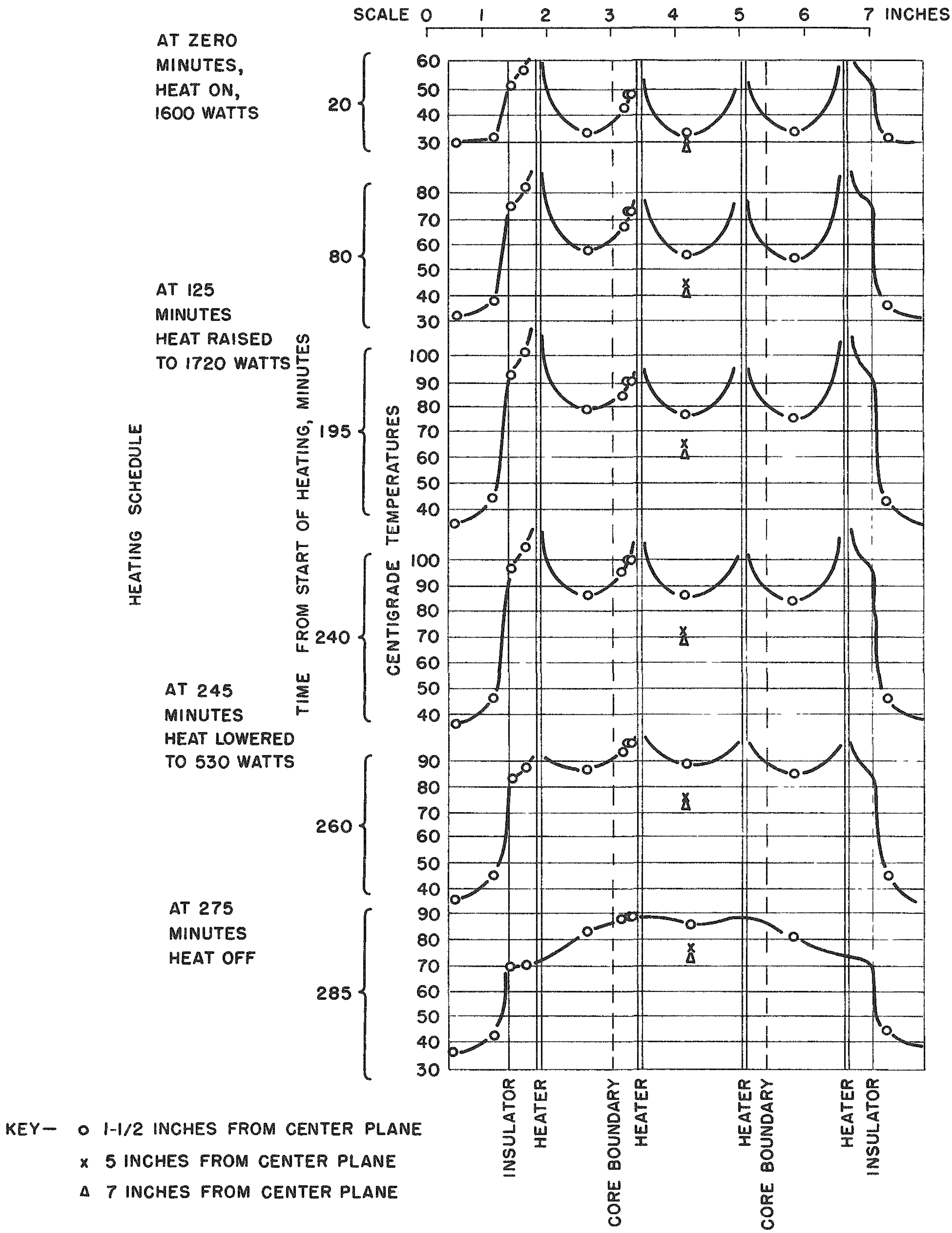


FIGURE 19
TEMPERATURE PROFILES —CORE AND INNER BLANKET HEATED

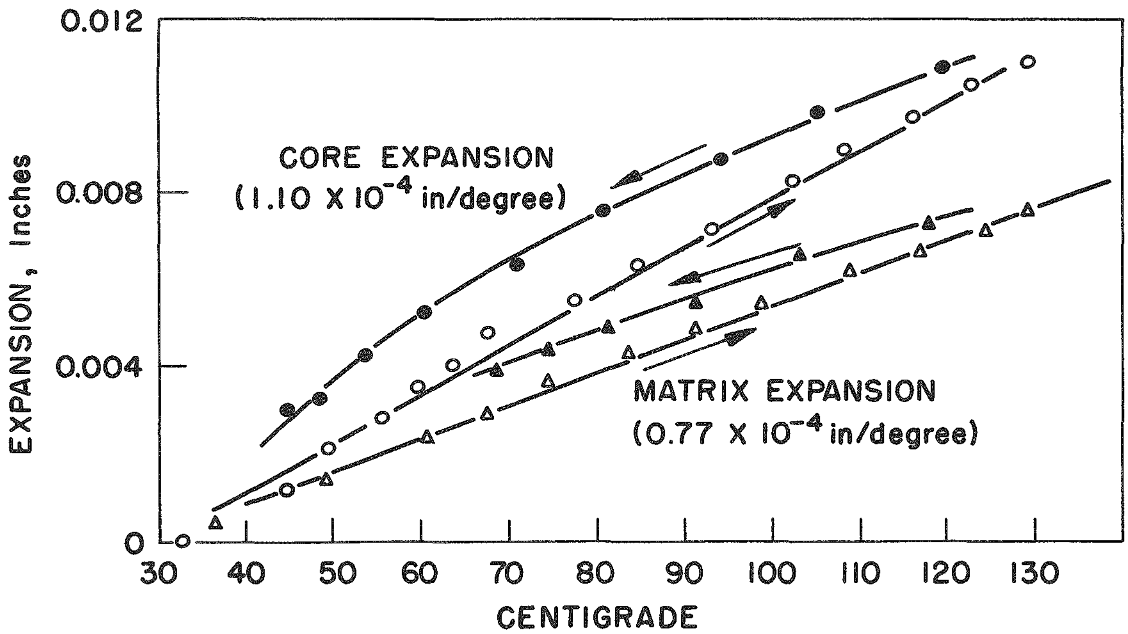


FIGURE 20
THERMOCOUPLE NO. 4
CORE HEATING

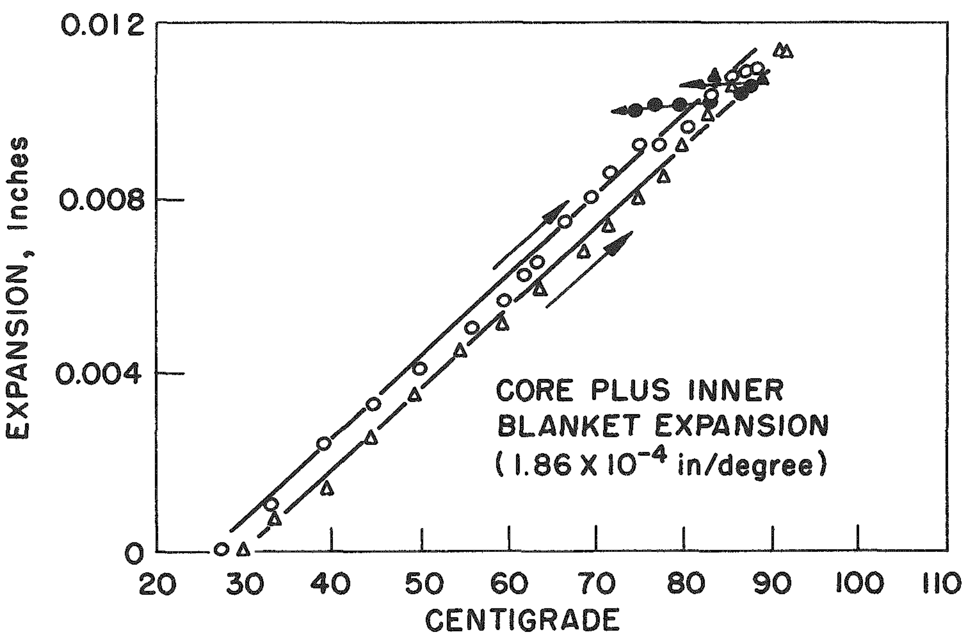


FIGURE 21
THERMOCOUPLE NO. 9
CORE PLUS INNER BLANKET HEATED